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(54) Optical waveguide embedded light redirecting and focusing bragg grating arrangement.

(57) An optical waveguide light redirecting arrangement includes an optical waveguide having a solid portion that guides light in a first path along a longitudinal axis, with at least one grating region being embedded in the solid portion at a location remote from its end portions. The grating region includes a multitude of grating elements extending at such longitudinal spacings and at such oblique angles relative to the longitudinal axis to redirect light reaching the grating elements between the first path and at least one second path extending externally of the waveguide and diverging between a focus situated at a predetermined distance from the waveguide and the grating region. When light is directed in one of the first and second paths toward the grating region, it is redirected by the grating elements into the respectively other of the second and first paths with attendant in-phase combination in the other path of light having a wavelength within a range around a central wavelength. The grating elements are formed in the waveguide by exposing the waveguide to an interference pattern of two ultraviolet radiation beams that are symmetrical with respect to a plane extending at the oblique angle relative to the waveguide axis at the center of the grating region.

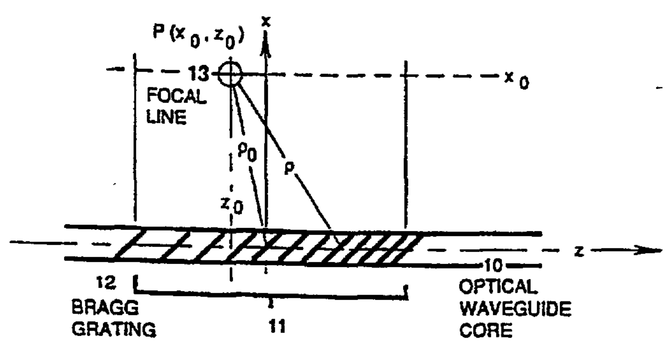

FIGURE 1

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OPTICAL WAVEGUIDE EMBEDDED LIGHT REDIRECTING AND FOCUSING BRAGG GRATING ARRANGEMENT

Technical Field

The present invention relates to optical waveguides in general, and more particularly to optical waveguides, especially fibers, that are provided with embedded light redirecting Bragg gratings, to optical systems utilizing such optical waveguides, and to methods of producing such optical waveguides.

Background Art

There are already known various constructions of optical waveguides, including optical fibers, that are provided with embedded gratings that are being used either for inserting light into or for removing light from the respective optical waveguide at an intermediate location or at different intermediate locations of the waveguide. So, for instance, the U.S. Patent No. 4,749,248 to Aberson, Jr. et al, issued on June 7, 1988, discloses a device for tapping radiation from, or injecting radiation into, a single mode optical fiber. This patent discloses that it is possible to convert a guided mode in an optical fiber into a tunnelling leaky mode or vice versa by forming a grating of appropriate periodicity at least in the core of the optical fiber, and either to remove the guided mode from the fiber core into the cladding by converting it into the leaky mode, and ultimately from the fiber altogether, or to insert light of an appropriate wavelength into the core to form a guided mode therein by directing light of a proper wavelength from the exterior of the fiber toward the grating to propagate in the fiber cladding and to be converted by the grating into the guided mode in the fiber core. It is disclosed in this patent that the grating may be formed mechanically or by exploiting the photoelastic or photorefractive effect; in either case, the grating is formed in such a manner that fiber core regions of identical optical properties are situated in planes oriented normal to the longitudinal axis of the optical fiber.

While this approach may achieve satisfactory results for some applications, it has an important disadvantage in that it results in very high losses of optical power coupled out of or into the optical fiber. This is at least partially attributable to the fact that, inasmuch as the grating is imposed normal to the longitudinal axis of the core, the conversion of the guided mode into the leaky mode or vice versa takes place with uniform distribution all around the fiber axis, so that a predominant proportion of the leaky mode is not captured by the sensing arrangement when this approach is being used to tap light out of the fiber, or bypasses the fiber core when this approach is being used to launch light into the core via the cladding mode and its conversion into the guided core mode at the grating.

It is also already known, for instance from the commonly owned U. S. Patent No. 4,725,110, issued on February 16, 1988, to impress periodic gratings into the optical fiber core by exposing the core through the cladding to the interference pattern of two coherent ultraviolet light beams that are directed against the optical fiber at two angles relative to the fiber axis that complement each other to 180°. This results in a situation where the grating is oriented normal to the fiber axis so that it reflects, of the light launched into the fiber core for guided propagation therein in a propagation direction, only that having a wavelength within a very narrow range, back along the fiber axis opposite to the original propagation direction so that such reflected light is guided in the core to the point at which the original light had been launched into the fiber core. On the other hand, this grating is transparent to light at wavelengths outside the aforementioned narrow band so that it does not affect the further propagation of such other light. It may be seen that this approach has its limitations as well in that it is not suited for removing meaningful amounts of light from or launching them into the fiber at any other location than the respective fiber ends.

This problem has been addressed in a commonly owned copending U. S. patent application Serial No. 07/456,450. [1)]The solution presented there involves writing the grating elements at an oblique angle relative to the longitudinal axis of the waveguiding region, such as of a fiber core, so that the thus formed grating redirects light between a first path extending longitudinally of the waveguiding region, and at least one second path extending between the grating and the exterior of the waveguide in a direction that depends on the axial wavenumber or wavelength of the light being so redirected. This second path is shown to have a dimension as considered in the longitudinal direction of the waveguide that substantially corresponds to the associated dimension of the grating, and an external lens is being used in the second path to either focus

1) Copy enclosed

the light emanating from the fiber or to collimate light issued by an external source onto the grating, depending on whether the grating is being used to tap light out of the waveguide or launch light into the waveguide. It will be realized that the need for providing such a lens, which typically has a complex configuration and thus is quite expensive, significantly increases the cost of the equipment and thus detracts from the commercial appeal of such equipment. Moreover, alignment problems may be encountered either during the initial set-up or during the operation of the equipment.

Accordingly, it is a general object of the present invention to avoid the disadvantages of the prior art.

More particularly, it is an object of the present invention to provide an optical waveguide with an embedded light redirecting arrangement which does not possess the disadvantages of the known arrangements of this kind.

Still another object of the present invention is to develop the light redirecting arrangements of the type here under consideration in such a manner as to obtain highly efficient coupling of light at a selected wavelength within a limited range between the optical waveguide core and a spatially limited path extending externally of the core and passing through a focus or focal region.

It is yet another object of the present invention to devise an optical system utilizing the embedded grating optical waveguide of the above type, which system is instrumental in providing for the efficient coupling of light into and out of the optical waveguide and focusing of such light.

Yet another object of the present invention is to design the system of the above type in such a manner as to be very simple in construction, inexpensive to manufacture, easy to use, and yet reliable in operation.

A concomitant object of the present invention is to develop a method of forming the embedded tap in the optical waveguide core, which method is highly efficient and reliable.

Disclosure of the Invention

In keeping with these objects and others which will become apparent hereafter, one feature of the present invention is embodied in an optical waveguide light redirecting arrangement which includes an optical waveguide having two spaced end portions, and including at least a waveguiding portion of a solid material capable of guiding light between the end portion in a first path extending along a predetermined axis. According to the invention, at least one grating region is embedded in the waveguiding portion at a location remote from the end portions, and has a multitude of grating elements extending at such spacings relative to one another as considered in the direction of the axis and at such oblique angles relative to the axis to redirect light reaching the grating elements between the first path and at least one second path extending externally of the waveguide and diverging between a focus and the grating region. There is further provided first optical means for directing light into one of the first and second paths and toward the grating region for redirection by the grating elements into the respectively other of the second and first paths with attendant in-phase combination in the other path of light having a wavelength within a range around a central wavelength, and second optical means for capturing the light propagating in the other path.

Another aspect of the present invention is a method of producing the grating region, which involves the exposure of the waveguiding portion to the interference pattern of two coherent ultraviolet radiation beams, where the angles of these beams with respect to the longitudinal axis of the waveguiding portion at the center of the grating region are selected in such a manner that the interference pattern fringes (e.g. intensity peaks) extend through the waveguiding portion at the aforementioned oblique angle and induce permanent variations in the refractive index of the waveguiding portion in dependence on the intensity of the fringes, thus forming the aforementioned grating elements. One of the interfering beams may have a curved phase front, or the grating region may be bent either during the formation of the grating, or during its use, to cause the grating elements to have the aforementioned focusing effect. Another series of refractive index variations may be imposed orthogonally to the first one for the grating to focus to a focal point. The present invention is also directed to a novel article of manufacture, that is, to an optical waveguide, especially an optical fiber, which is provided with at least one of the above-discussed redirecting grating regions that is produced by resorting to the above-discussed method of the present invention.

Brief Description of the Drawing

The present invention will be described in more detail below with reference to the accompanying drawing in which:

Figure 1 is a considerably enlarged axial sectional view of an optical fiber provided with an embedded grating region in accordance with the present invention for use in redirecting light into or out of the fiber core with passage of such light through a focus external of the fiber;

Figure 2 is a view similar to that of Figure 1 but showing the optical fiber as extending in a curved course during the formation or use of the grating region;

Figure 3 is a view similar to that of Figure 2 but showing an arrangement employing two of the fibers of Figure 2 arranged oppositely to one another and one issuing light into and the other receiving light from a focal region thereof;

Figure 4 is a considerably enlarged partially broken away perspective view of a waveguide provided with a grating formed by two orthogonal systems of refractive index variations to have a focal point for its focus; and

Figure 5 is a graphic representation of the dependence of the change in the refractive index on distance from the center of the waveguide, taken on line A - A of Figure 4.

Best Mode for Carrying Out the Invention

Referring now to the drawing in detail, and first to Figure 1 thereof, it may be seen that the reference numeral 10 has been used therein to identify an optical waveguide. The optical waveguide 10 is shown to be configured as an optical fiber core, of which only a relatively short longitudinal portion is depicted. If so desired, a non-illustrated fiber cladding could be arranged, as is well known in the optical fiber field, around the fiber core 10. The fiber core 10 incorporates a grating region 11 that includes a multitude of grating elements 12.

At this juncture, it may be appropriate briefly to describe the arrangement disclosed in the aforementioned U. S. patent application Serial No. (Docket R-3258), as much of which as needed to fully appreciate and/or understand the present invention is incorporated herein by reference, so as to aid in understanding the problem with which the present invention successfully deals. In that arrangement, each of the grating elements extends at substantially the same oblique angle α with respect to the longitudinal axis of the core, and the grating elements are spaced the same distance from one another as considered in the longitudinal direction of the optical fiber. The grating elements are formed in the grating region of the core, which is preferably of a germanium-doped silica or similar glass that is capable of having the grating elements written, impressed or otherwise applied or embedded therein, by application of an interference pattern of two ultraviolet radiation beams to the core. The thus produced periodic grating elements then constitute refractive index perturbations that are permanently induced in the core by exposure to ultraviolet radiation. This method makes use of a first order absorption process in response to transverse irradiation of the fiber 10 with light in the ultraviolet absorption band of the core material. Inasmuch as the grating is formed by illuminating the core from the side, preferably through the cladding and without affecting the latter, with two coherent beams that are incident on the optical fiber symmetrically to a plane extending at the oblique angle α with respect to the longitudinal axis of the core, the intensity peaks of an interference pattern resulting from interference of the coherent incident beams, and thus the grating elements, extend parallel to this plane and the spacings between the grating elements are the same. Such exposure induces permanent refractive index changes in the grating region, in effect creating a phase grating effective for redirecting light reaching the grating.

While only a quite small portion of the light propagating through the fiber core or being launched into the core is redirected at each of the grating elements as a result of the refractive index changes attributable to the presence of the grating elements, subsequently to either leave the optical fiber or to be launched into the core for guided longitudinal propagation therein, respectively, the cumulative effect of the grating elements is the redirection of a significant proportion of the light the wavelength of which is in a very narrow range around the center wavelength λ that is in a predetermined ratio to the periodicity of the grating elements. Furthermore, the light within the narrow range that is thus redirected at any one of the grating elements out of the optical fiber is in such a phase relationship with respect to the light redirected at any other of the grating elements that the cumulative redirected light beam has a substantially planar wavefront so that substantially none of the thus escaping redirected light is lost to destructive interference or diffraction. Moreover, the thus escaping redirected light beam propagates outside the optical fiber along a single direction determined by the aforementioned oblique angle α, albeit with some fanning out in the circumferential direction, rather than all around the optical fiber; this facilitates the capture of the thus escaping light and increases the proportion of such light that is actually captured.

By the same token, when coherent light is being launched into the optical fiber core, it is sufficient to direct all of the power of such light all over the grating region along a single direction substantially coincident with the aforementioned path and including the requisite angle α with the longitudinal axis of the core, rather than having to distribute such power all around the optical fiber and, to the extent that such power is carried by light having a wavelength within the aforementioned narrow range around the center

wavelength λ, a meaningful proportion of such directed light power will be redirected into the core for guided longitudinal propagation therein even though only a small portion of such light is redirected at each of the grating elements. This effect is attributable to the constructive interference between the partial light amounts which have been redirected at the respective grating elements with the partial light amounts redirected at the longitudinally consecutive ones of the grating elements. The constructive interference is not limited to a single value of the central wavelength λ; however, the angle of the external path that results in the constructive interference is peculiar to the respective central wavelength λ.

The arrangement described in the above patent application, as advantageous as it may be for some uses, has a considerable disadvantage that, inasmuch as the grating region occupies a finite and yet relatively significant length of the core and the partial light amounts redirected by the grating elements into the external path propagate substantially parallel to one another, the dimension of the external path that is parallel to the longitudinal core axis is substantially identical to the axial length of the grating region. To achieve efficient capture of the light emitted into the second path, the above patent application proposes the use of an external lens or of functionally similar external optical elements to concentrate or focus such partial light amounts onto a photodetector or another light receiver component. Conversely, light issued by an external source must be collimated prior to reaching the grating region and expanded to cover the entire grating region to efficiently launch light into the core, by external optics akin or identical to those described above. This complicates the structure of the arrangement, substantially increases its cost, and may result in alignment problems.

Turning now once more to Figure 1 of the drawing, it is to be mentioned first that the concepts shown therein (as well as in the remaining Figures of the drawing) are based on the principles described above. Here again, the grating elements 12 are inscribed in the core 10 by exposing the grating region of the latter to an interference pattern of two incident ultraviolet light beams; however, unlike in the situation described above, the grating 11 has additional quadratic refractive index variations impressed therein.

A direct way of inscribing the grating 11 of the type revealed in Figure 1 of the drawing in accordance with the present invention is by exposing the waveguide or core 10 to incident ultraviolet radiation beams at least one of which has a suitable phase front curvature, for instance, as a result of passage of the affected incident beam through an appropriately configured lens. In this context, it is to be mentioned that the in-fiber Bragg grating 11 can be thought of, and modeled as, a linear-phased array. Refractive index variations redirect a small fraction of an incident bound mode into a radiation pattern that is determined by the grating element period tilt, and grating region length, the light wavelength, the waveguide cross section and the mode spectrum. If the grating period Λ is a constant, as it is in the arrangement of the above-discussed patent application, then the emission pattern is a narrow, conical diverging fan-shaped intensity distribution. In accordance with the present invention, this pattern is focused to a focal line in the near field by varying the grating period or wavenumber $K = 2\pi/\Lambda$. As indicated in Figure 1 of the drawing, a grating 11 having a linearly varying grating wavenumber or quadratic phase focuses the narrow diverging fan to a line focus at a point $P(x_o, z_o)$ in the longitudinal plane of the waveguide 10, thus creating the effect of a Fresnel lens. It is known, for instance, from the book by A. W. Snyder and J. D. Love entitled "Optical Waveguide Theory", Chapter 22, pp. 460 - 463, published by Chapman & Hall (1983), that weak index perturbations in a fiber core act as a distribution of point current dipoles, with phase and amplitude prescribed by the bound mode form and the grating period (or wavenumber) and strength. In the Fresnel zone, near to the fiber, the diffraction field $G(x_o, z_o)$ in the longitudinal plane can be expressed in terms of a Fresnel transform:

$$G(x_o, z_o) \approx \int_{-L/2}^{L/2} e^{j(K-\beta)x} \cdot e^{jknx^2/2z_o} \cdot e^{-jkn(xx_o/z_o)}\, dx$$

wherein n denotes the refractive index of the cladding, L is the length of the grating, k is the free space wavenumber, and β is the propagation constant of the bound mode.

If we let $K = K_o + knx/2z_o$, then

$$G(x_o, z_o) = \int_{-L/2}^{L/2} e^{j[(K_o-\beta) - knx_o/z_o]x} dx =$$

$$= \operatorname{sinc}\{[(K_o-\beta) - knx_o/z_o]L\} \approx$$

$$\approx \delta\{[(K_o-\beta) - knx_o/z_o]L\}.$$

It may be seen from the above that the light is brought to a line focus at $P(x_o, z_o)$ where the angle $\arctan(x_o/z_o)$ is determined by the values of K_o, and kn, as is the case in unfocused grating tap, and the position z_o is determined by the sweep rate of K. Given the reciprocal effect of the grating 11, if light of the proper wavelength issued by an external sóurce is caused to pass through and focus onto the focal line P-(x_o, z_o) on its way to the grating 11, the latter will redirect or launch such light into the waveguide 10 for longitudinal propagation therein.

Similar focusing effect of the grating 11 is achieved if at least the grating region of the optical fiber or waveguide 10 is bent along a circular arc or any other suitable concave curve, either while the grating 11 is being written by exposure to the incident ultraviolet radiation beams symmetrical with respect to the plane extending at the angle α relative to a tangent to the longitudinal axis of the waveguide 10 at the center of the grating 11, or during the use of the waveguide after the grating 11 has been inscribed with the waveguide 10 extending along a straight course, as indicated in Figure 2 of the drawing. Here, the phase variation is introduced by bending the waveguide 10 into a circular arc having a radius of curvature ρ c.

When the grating period and tilt are set to redirect the light perpendicularly of the waveguide axis, the bending of the fiber focuses the pattern along a line at $\rho_f = \rho_c$.

Figure 3 of the drawing illustrates an optical arrangement that utilizes two waveguides 10 and 10' of the type described above, that is, each provided with the varying phase grating 11 or 11', one for illuminating an object 13 situated at and around the focal line $P(x_o, z_o)$ thereof, and the other for capturing light passing through (such as in measuring turbidity or the like) or radiated by (such as in measuring fluorescence) the object 13. The gratings 11 and 11' may both redirect light of the same wavelength, or each may redirect light of a different wavelength, depending on the parameter being measured. It will be seen that the amount of light received by the other of the waveguides 10 and 10' is an indication of the magnitude of the parameter being measured.

The arrangements as described so far focus the emitted light escaping from the waveguide 10 to a focal line. However, as alluded to before, the thus escaping light forms a fan spreading in the circumferential direction of the waveguide 10 when the latter is constituted by an optical fiber. Under some circumstances, however, it may be desirable to focus such escaping light to a focal point rather than to a focal line. This can be accomplished, especially if the waveguide 10 is a multimode waveguide, in a manner depicted in Figure 4 of the drawing, where it is indicated that at least partial Fresnel focusing can also be achieved in the plane orthogonal to the original Bragg plane by imposing a secondary quadratic phase variation into the waveguide 10 by exposure of the latter at the grating region 11 to another pair of interfering ultraviolet light beams. A graph of refractive index variation across the waveguide 10, taken on line A - A of Figure 4, is presented in Figure 5.

A particular advantage of the unidirectional focused redirection is not only the removal of at least a significant amount of the light of the selected narrow wavelength band around λ from the spectrum allowed to propagate through the waveguide 10 beyond the grating region 11 when the latter is being used for tapping light out of the fiber core 10, or insertion of such light into the core 10 when the grating region 11 serves to launch light into the fiber 10, but also, and possibly more importantly, an easy capture of the tapped-out redirected light in the narrow wavelength band around λ after its escape from the fiber 10 at the grating region location that may be situated a considerable distance from either one of the ends of the fiber 10, or easy insertion of such light into the fiber core 10 at such remote location, without the use of any external lenses or similar external focusing arrangements. Thus, the grating region 11 including the inclined grating elements 12 of the present invention constitutes a wavelength selective tap in the optical fiber 10 and also simultaneously focuses such light to a focus (either a focal line or a focal point) when used as a

tap, or launches external light passing through such a focus on its way to the grating 11 into the waveguide 10 for longitudinal propagation therein.

While the present invention has been illustrated and described as embodied in a particular construction of an optical waveguide and associated equipment, it will be appreciated that the present invention is not limited to this particular example; rather, the scope of protection of the present invention is to be determined solely from the attached claims.

Claims

1. An optical waveguide light redirecting and focusing arrangement comprising:
an optical waveguide having two spaced end portions, and including at least a waveguiding portion of a solid material capable of guiding light between said end portions in a first path extending along a predetermined axis;
at least one grating region embedded in said waveguide portion at a location remote from said end portions and having a multitude of grating elements extending at such respective spacings as considered in the direction of said axis and at such respective oblique angle relative to said axis as to redirect light reaching said grating elements between said first path and at least one second path extending externally of said waveguide and diverging between a focus situated at a predetermined distance from said optical waveguide and said grating region;
first optical means for directing light into one of said first and second paths and toward said grating region for redirection by said grating elements into the respectively other of said second and first paths; and
second optical means for capturing the light propagating in said other path.

2. An embedded light redirecting and focusing grating optical waveguide comprising:
an optical waveguide having two spaced end portions, and including at least a waveguiding portion of a solid material capable of guiding light between said end portions in a first path extending along a predetermined axis;
at least one grating region embedded in said waveguide portion at a location remote from said end portions and having a multitude of grating elements extending at such respective spacings as considered in the direction of said axis and at such respective oblique angle relative to said axis as to redirect light reaching said grating elements between said first path and at least one second path extending externally of said waveguide and diverging between a focus situated at a predetermined distance from said optical waveguide and said grating region.

3. A method of forming an embedded optical light redirecting and focusing grating in a selected grating region of an elongated solid portion of an optical waveguide, comprising the steps of:
forming two mutually coherent beams of ultraviolet radiation at least one of which has a curved phase front; and
directing the two beams transversely on the solid portion at respective angles of incidence selected for the beams to be symmetrical relative to a plane extending at an oblique angle relative to a longitudinal axis of the solid portion for the two beams to coherently interfere with one another with attendant generation of an interference pattern having intensity peaks that extend into and through said grating region and form therein a multitude of permanently embedded grating elements that are so oriented and spaced from one another as to redirect light reaching them between a first path extending longitudinally through the solid portion and at least one second path extending externally of the waveguide and diverging between a focus situated at a predetermined distance from said waveguide and said grating region.

4. A method of forming an embedded optical light redirecting and focusing grating in a selected grating region of an elongated solid portion of an optical waveguide, comprising the steps of:
forming two mutually coherent beams of ultraviolet radiation;
directing the two beams into a spatial region at such respective angles as to be symmetrical relative to a plane of symmetry with attendant formation of an interference pattern having intensity peaks extending parallel to said symmetry plane in said spatial region;
placing the grating region into said spatial region in such an orientation that said plane extends at a predetermined oblique angle with respect to an axis of the solid portion substantially centrally of the grating region for said interference pattern to extend into and through the solid portion with attendant

formation of grating elements constituted by periodically repetitive refractive index variations in the grating region in dependence on intensity variations of said interference pattern;
positioning the grating region at a location of use; and
causing said grating region to extend along a curved course during one, and a straight course during the other, of said placing and positioning steps for said grating elements to be so oriented and spaced from one another during the use thereof at said location of use as to redirect light reaching them between a first path extending longitudinally through the solid portion and at least one second path extending externally of the waveguide and diverging between a focus situated at a predetermined distance from said waveguide and said grating region.

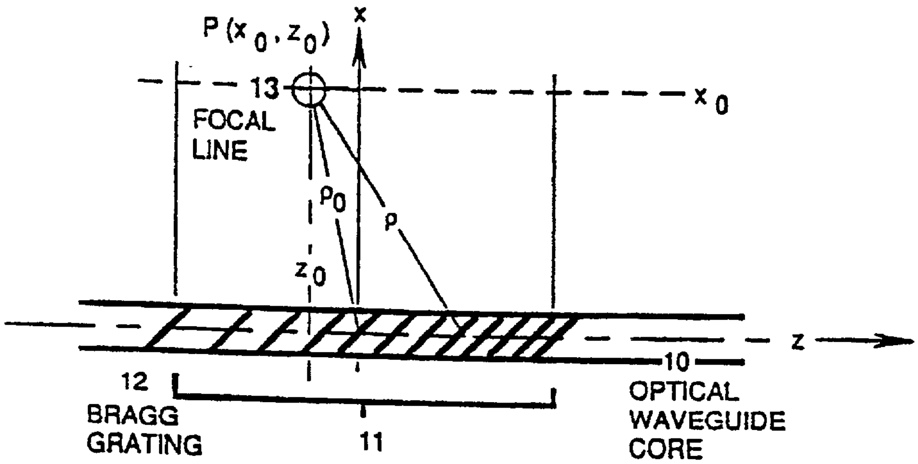

FIGURE 1

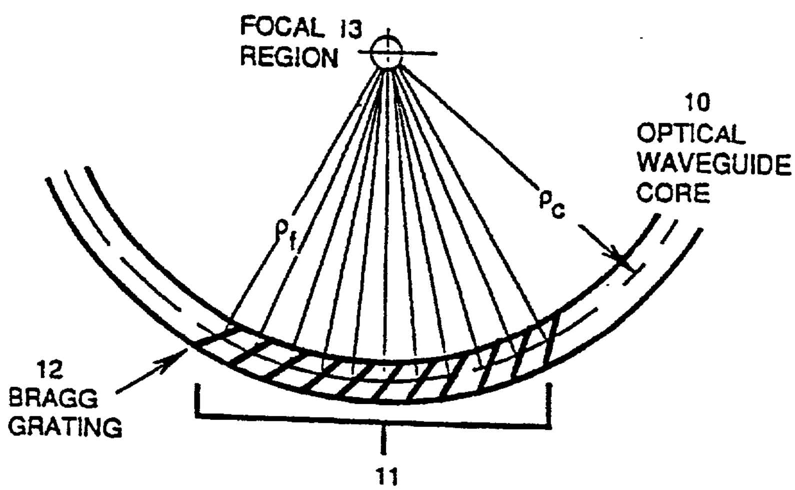

FIGURE 2

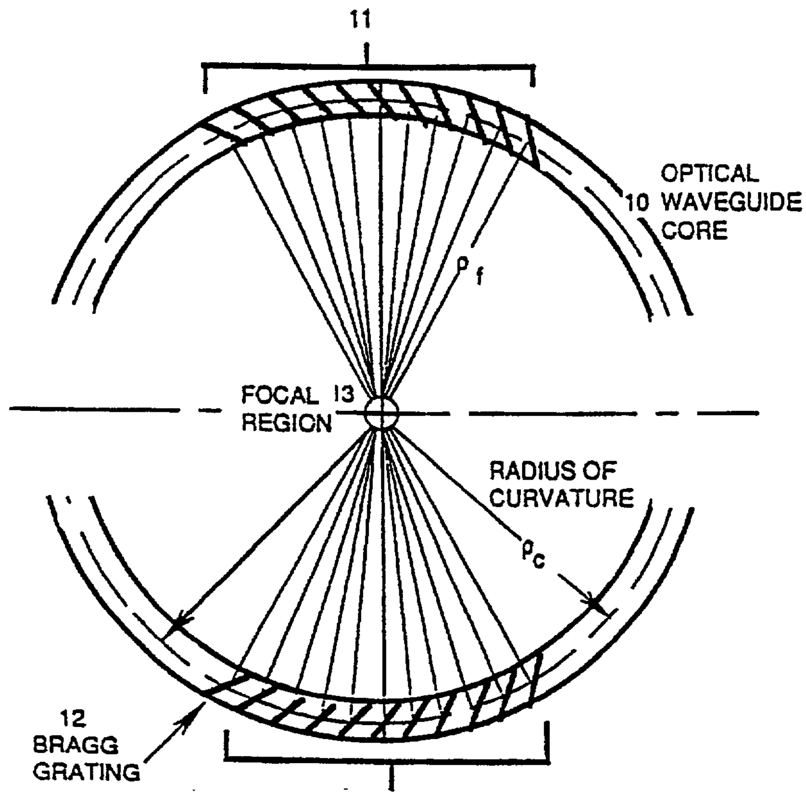

FIGURE 3

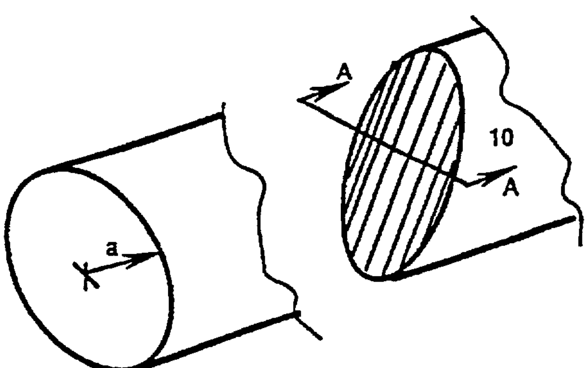

Figure 4

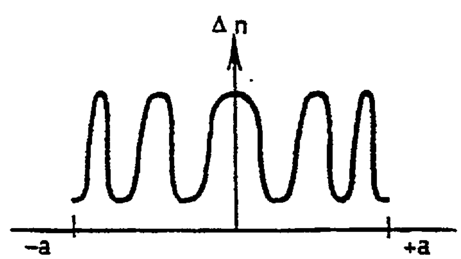

Figure 5

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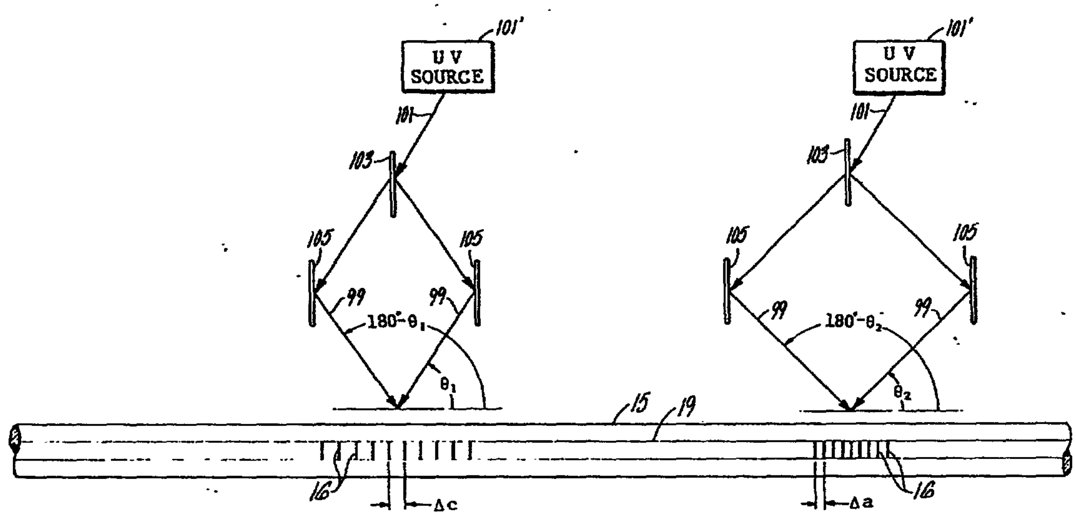

(57) Abstract

A method of establishing a dielectric periodic index of refraction phase grating (16) upon the core (19) of an optical waveguide (15) by intense angled application of several tranverse beams (99) of ultraviolet light, enabling the establishment of a distributed, spatially resolving optical fiber strain gauge (13).

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Method For Impressing Grating Within Fiber Optics

Technical Field

This invention relates to impressing, establishing, printing or writing phase gratings in optical fibers or waveguides and the optical detection and measurement of strain distributions with multi-wavelength light provided to said phase gratings.

Background Of the Invention

It is known to determine the distribution of axial strain or temperature along the length of a fiber optic sensor according to the technique described by S. K. Yao et al. in 21 Applied Optics (1982) pages 3059-3060. According to this technique, very small deformations at the interface between an optical core and its cladding will cause light measurably to couple from core to cladding modes. This permits measurements by time-domain reflectometry or a series of cladding taps to determine transmission loss and the distribution of applied perturbations.

Disclosure of Invention

According to the invention, phase gratings are impressed along the core of an optical waveguide by the application of intense beams of ultraviolet light

transverse to th axis of the core at selected angles of incidence and the complements thereto.

Brief Description of the Drawing

Fig. 1 is a schematic drawing of the spatially resolving optical fiber strain gauge according to the invention addressed herein;

Figs. 2A through 2C are partial schematics of selected sections of the optical waveguide including its cores, indicating grating patterns of varying spacing corresponding to selected regions A, B and C in a mechanical structure being monitored for strain;

Fig. 3 is a graph of the intensity spectrum of the reflected light produced by injecting broadband light into the core of the waveguide with shifts in the spectral lines indicating strain at specific stations; and

Fig. 4 shows a schematic illustration of a technique for establishing a grating pattern of variable spacing at selected positions along the length of the optical waveguide.

Best Mode for Carrying Out the Invention

Fig. 1 shows a schematic diagram of the spatially resolving optical fiber strain gauge 13. The gauge 13 includes an optical waveguide 15 or fiber operative to transmit a single or lowest order mode of injected light.

The core 19 of waveguide 15 is preferably a Germanium-doped silica or glass filament. The core 15 contains a series of variable spacing Bragg reflection gratings 16 written, impressed or otherwise applied by application of a variable

two-beam ultraviol t (less than 300 nanometer) interference pattern. These periodic gratings 16 or refractive index perturbations are permanently induced by exposure to intense radiation.

Figs. 2A through 2C shows the establishment of different wavelength gratings 16 corresponding to respective locations on core 19.

Each of selected gratings 16 is formed by transverse irradiation with a particular wavelength of light in the ultraviolet absorption band of the core material associated with a position in a structural component 22. This procedure establishes a first order absorption process by which gratings 16 each characterized by a specific spacing and wavelength can be formed by illuminating core 19 from the side with two coplanar, coherent beams incident at selected and complementary angles thereto with respect to the axis of core 19. The grating period is selected by varying the selected angles of incidence. Thus, a permanent change in the refractive index is induced in a predetermined region of core 19, in effect creating a phase grating effective for affecting light in core 19 at selected wavelengths.

As indicated in Fig. 1 the optical waveguide 15 and core 19 are attached or embedded in a section of structural component 22, in particular a plate for example. Core 19 contains characteristic periodic refractive index perturbations or gratings 16 in regions A, B and C thereof. A broadband light source 33 or tunable laser is focused through lens 33' onto the exposed end of core 19. A beam splitter 34 serves to direct the return beam from core 19 toward

a suitable readout or spectrometer 37 for analysis. Alternatively, a transmitted beam passing out of the end 19' of core 19 could be analyzed.

The spectrum of the reflected light intensities from strain gauge 13 is shown in Fig. 3. A complementary tranmitted spectrum is also established passing out of the end 19' of core 19. The spectrum contains three narrowband output lines centered at respective wavelengths: $lambda_A$, $lambda_B$ and $lambda_C$. These output signals arise by Bragg reflection or diffraction from the phase gratings 16 at respective regions A, B and C. In this example, regions A and C of structural component 22 have been strained by deformation, causing a compression and/or dilation of the periodic perturbations in the fiber core.

As a result, the corresponding spectral lines are shifted as shown in Fig. 3 to the dotted lines indicated. The respective wavelength differences delta $lambda_A$ and delta $lambda_C$ are proportional to strain in respective regions A and C.

Fig. 4 illustrates the formation of periodic perturbations or gratings 16 in a region of fiber core 19 in response to exposure of core 19 to intense transverse ultraviolet radiation. Grating spacings Δ a and Δc are controlled by the incidence angle of incident interfering beams 99 and beam 101. As can be seen, the angles of incidence of beams 99 are complements (i.e. their sum equals 180 degrees) to each other with respect to the axis of core 19. The incident pair of beams 99 can be derived from a single incident beam 101 passing in part through a beam splitter 103 and reflecting from spaced parallel

reflectors 105. By increasing the separation between reflectors 105 and correspondingly varying the angles of incidence of beam 101, the angles of incidence of beams 99 upon core 19 can be controlled. Accordingly, the fringe spacing in grating 16 is varied as desired along the length of core 19, to permit a determination of strain or temperature corresponding to location along gauge 13.

Several spacings can be superimposed or colocated by this technique for the response set forth below.

Sensitivity to external perturbations upon structural component 22 and thus also upon core 19 depends upon the Bragg condition for reflected wavelength. In particular, the fractional change in wavelength due to mechanical strain or temperature change is:

$$d(\text{lambda}_i)/\text{lambda}_i = (q + \alpha)\Delta T + (1 + [\partial n/\partial \epsilon]/n)\epsilon$$

$$\simeq + 8 \times 10^{-6}/^{\circ}C$$

$$+ 8 \times 10^{-7}/\text{microstrain, where:}$$

q is the thermooptic coefficient, which is wavelength dependent;

α is the expansion coefficient;

ϵ is the axial or longitudinal strain;

lambda_i is the wavelength reflected by the grating at location i along the core 19;

n is the refractive index of the optical waveguide; and

ΔT is the change in temperature.

This relationship suggests a way to compensate for temperature changes along the length of the fiber sensor. In particular, if superimposed gratings of different spacings are provided, each of the two gratings will be subject to the same level of strain, but the fractional change in wavelength of each grating will be different because q is wavelength dependent.

Accordingly, each pair of superimposed gratings will display a corresponding pair of peaks of reflected or transmitted intensity. Accordingly, the shifts of these peaks due to a combination of temperature and strain can be subtracted. The shifts in these peaks due to strain will be the same in magnitude. Accordingly, any remaining shift after subtraction is temperature related. Thus, when it is desired to know the strain difference as between several locations possibly subject to a temperature difference, the temperature factor can be compensated.

The relationship therefore permits compensation for temperature variation during measurement, since the photoelastic and thermoptic effects are wavelength dependent. In other words, by superimposing two or more gratings at each location of interest, two or more spectral lines are established at each point of measurement. Strain will affect both lines equally; temperature will not. Thus, sufficient information is available to permit determination of the magnitude of strain and the temperature difference.

The information above is lik ly to cause others skilled in the art to conceive of other variations in carrying out the invention addressed herein, which nonetheless are within the scope of the invention. Accordingly, reference to the claims which follow is urged, as those specify with particularly the metes and bounds of the invention.

Claims

1. A method of impressing selected regions of the core of an optical waveguide with periodic dielectric index of refraction variation upon said core, comprising the steps of positioning each of said regions of core under a coherent light source of intense ultraviolet radiation; and

directing respective first and second coherent, coplanar beams, of said intense ultraviolet light transversely upon selected portions of said core at selected angles of incidence and its complement with respect to the axis of said core.

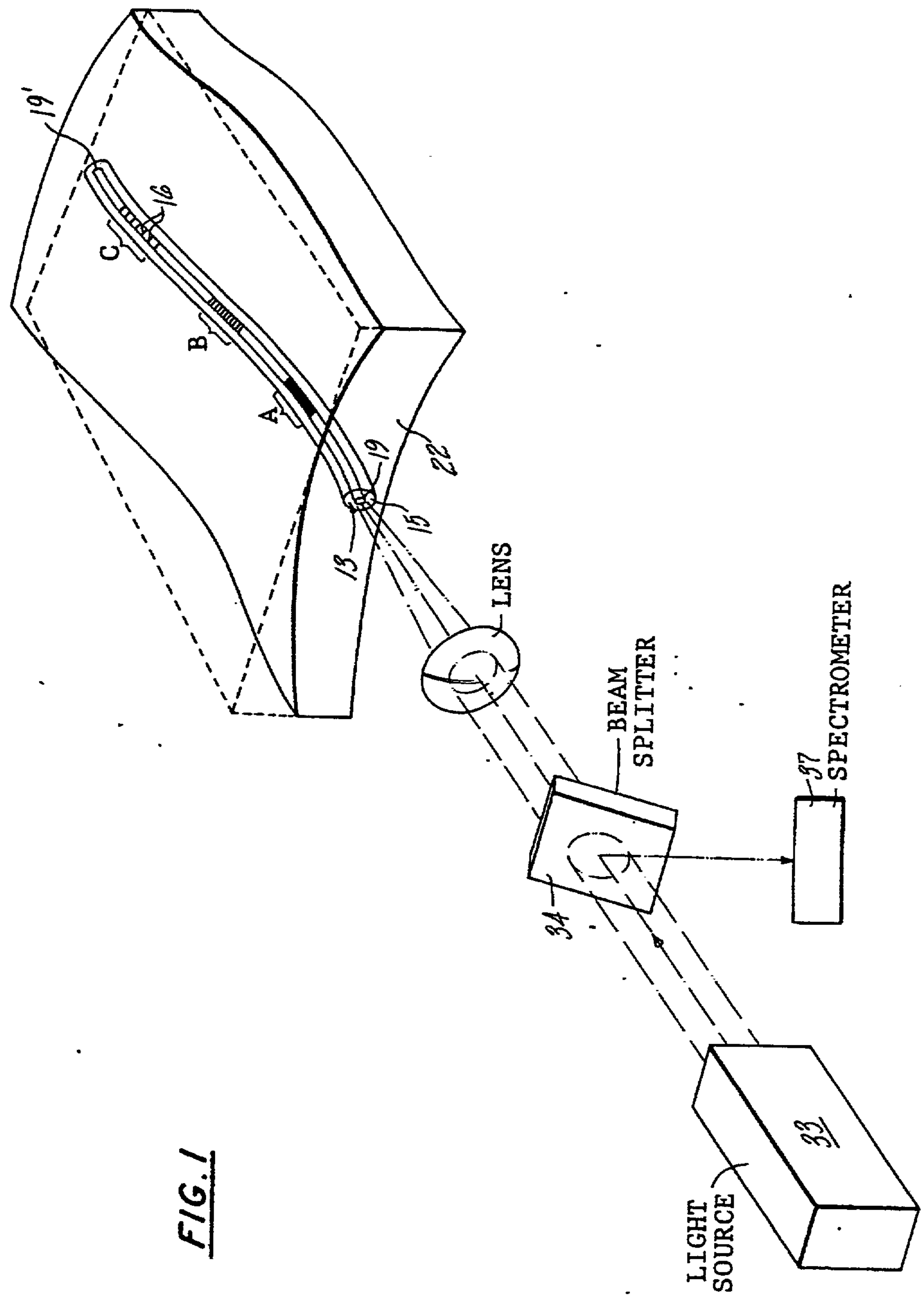

19'
16
C
B
A
19
22
15'
13
LENS
BEAM
SPLITTER
97
SPECTROMETER
34
33
LIGHT
SOURCE

FIG. 1

FIG. 2A

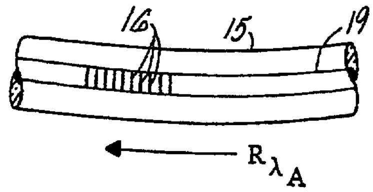


FIG. 2B

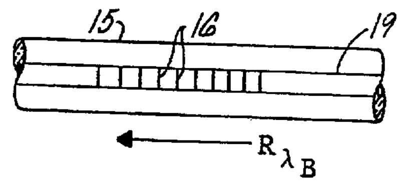


FIG. 2C

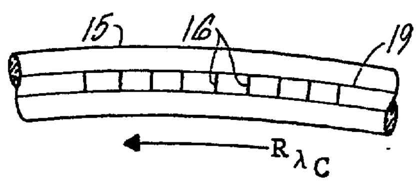
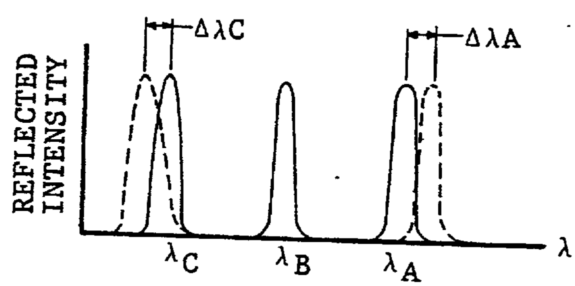


FIG. 3



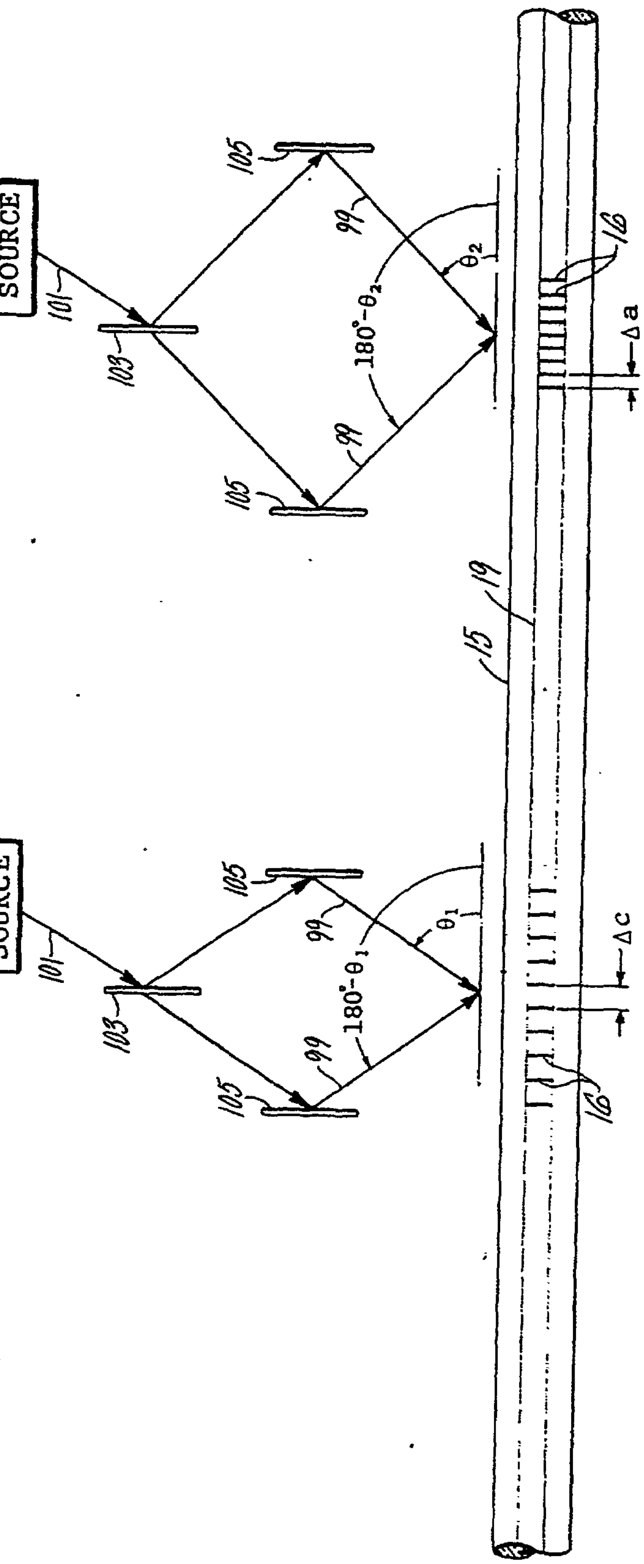

UV SOURCE
101'
101
103
105
99
180°-θ2
θ2
16
Δa
19
15
UV SOURCE
101'
101
103
105
99
180°-θ1
θ1
Δc
16

FIG. 4

INTERNATIONAL SEARCH REPORT

International Application No PCT/US85/01451

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

INT. CL[4] G 02B 5/18; G02B 6/34

US CL 350/96.19; 350/162.2

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S.	350/3.7, 96.19, 162.17, 162.2, 162.21

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
Y	US, A, 4, 286, 838 (Huignard et al.) 01 September 1981	1
Y	JP, A, 55-110, 207 (Segawa) 25 August 1980	1
Y	US, A, 4, 093, 339 (Cross) 06 June 1978	1
Y	US, A, 3, 891, 302 (Dabby et al.) 24 June 1975	1

* Special categories of cited documents: [15]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
15 October 1985	23 OCT 1985
International Searching Authority [1]	**Signature of Authorized Officer [20]**
ISA/US	William Propp